Baseline Calibration of the GeoSAR Interferometric Mapping Instrument

by

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Overview

- GeoSAR System Description
- Onboard Baseline Metrology Measurements
- Calibration Methodology
- Least Squares Estimation Specifics
- Calibration Site
- Baseline Estimation Results

Overview of GeoSAR

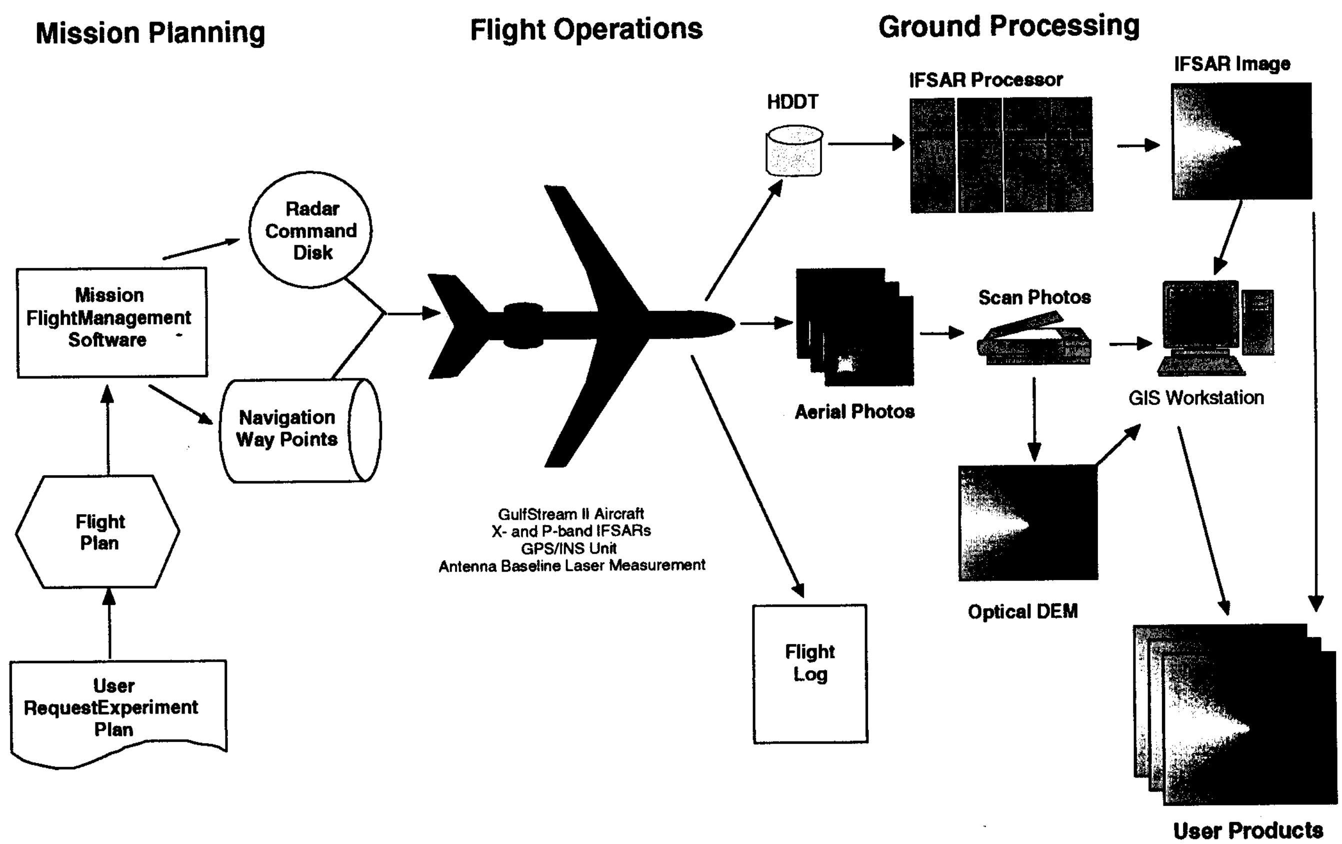
- Aircraft-based, interferometric synthetic aperture radar (SAR) system for topographic mapping.
  - Gulfstream II business jet
  - Day/night, all-weather, low-cost, commercial system
- Develop precision foliage penetration mapping technology based upon dual frequency, dual polarimetric, interferometric radar.
  - X-band radar (λ=3 cm) for bare ground and "tops" of trees
  - P-band (UHF) radar (λ=86 cm) for ground and foliage penetration (HH,HV)
- Produce true ground surface digital elevation models suitable for a wide variety of applications.
  - Combination yields "true ground surface" (TGS)
- Consortium of three agencies, initially funded by DARPA, current funding by NIMA.
  - Caltech's Jet Propulsion Laboratory (JPL), Pasadena, CA
  - Calgis, Inc., Fresno, CA
  - California Department of Conservation (CalDOC)

Calgis   Department of Conservation   JPL   NASA

Mapping System

- Mapping System Consists of:
  - Aircraft platform to host data collection hardware (Gulfstream II)
  - Flight planning software
  - Dual frequency (X-band/UHF) interferometric SARs
    - Single polarization @ X-band
    - Dual polarization @ UHF
    - Automated radar control
  - Laser interferometric baseline measurement system augmented with embedded GPS/INU systems and differential GPS for precision reconstruction of aircraft flight trajectory and attitude history
  - SAR processors capable of producing DEMs @ X-band and UHF and a true ground surface DEM from combined X-band/UHF analysis
  - A GIS system to analyze digital data

GeoSAR End-to-End System



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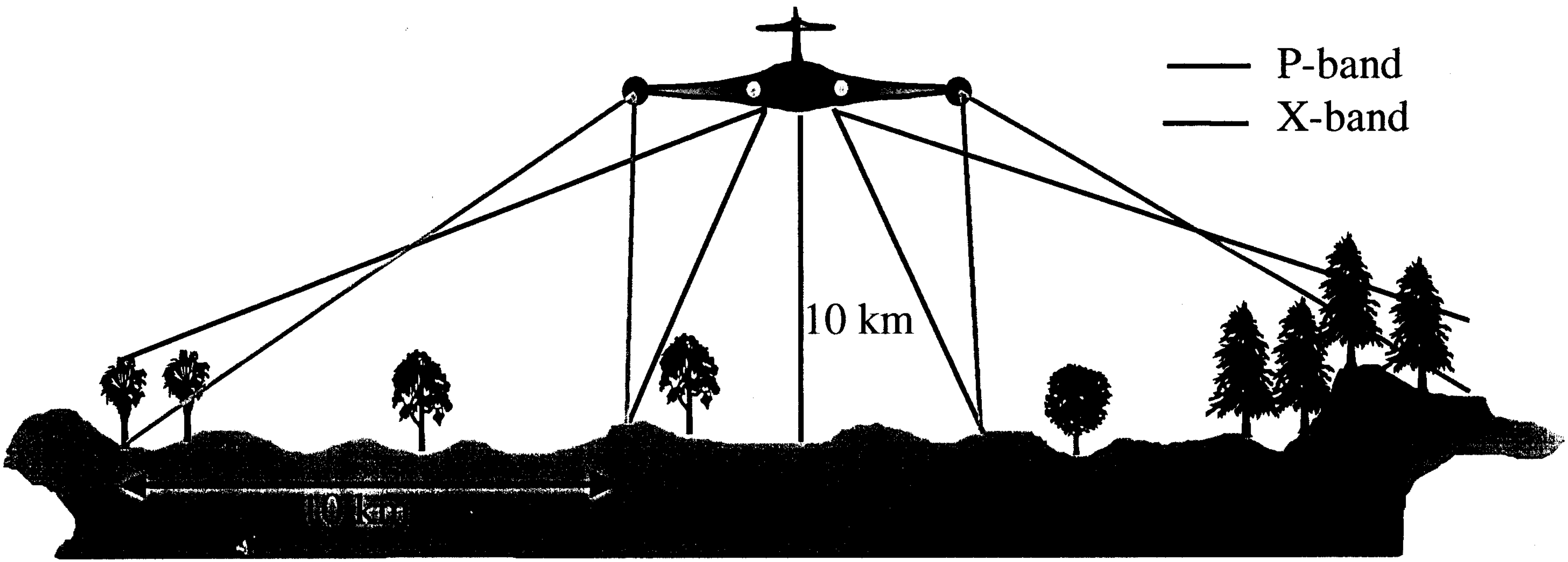
Data Collection Basics

- Nominally, GeoSAR will collect X and P-band data from both the left and right sides of the aircraft. Data is recorded on two SONY 512 Mb/s recorders.
- X-band data can be collected using either Ping-Pong or Non Ping-Pong mode depending on the amount of topographic relief.
- Data can be collected either using 80 or 160 MHz bandwidth modes. Data collected at 160 MHz is converted to 4-bit BFPQ data to reduce the data rate.



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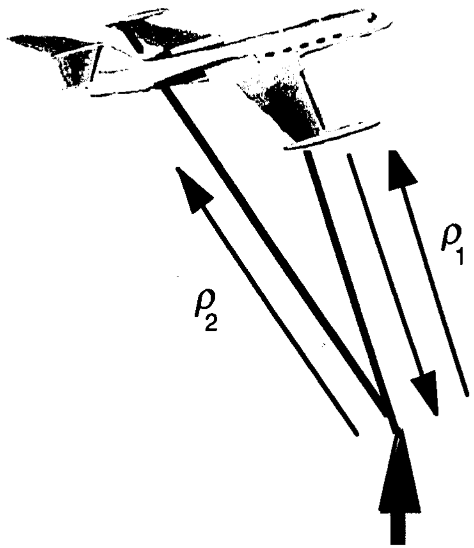
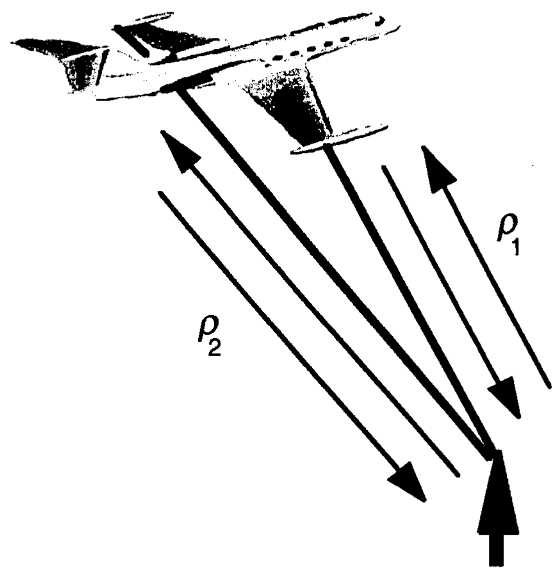
Two Methods of Data Collection

Non Ping-Pong



Transmission from one antenna
Reception through both antennas simultaneously

Ping-Pong



Alternately transmitting out of two antennas
Reception through the same antenna used for transmission only

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System Parameter Overview

UHF SYSTEM PARAMETERS

Parameter	Value
Peak Transmit Power	4 KW
Bandwidth	80/160 Mhz
Pulse Length	40 µsec
Sampling	8/4 BFPQ @ 160 MHz 8 bit for 80 MHz
Antenna Size	1.524 m x 0.381 m
Antenna Gain at Boresight	11 dBi
Antenna Look Angle	27 - 60 Deg
Antenna Boresight	60 Deg
Wavelength @ Center Frequency	0.86 m for 160 MHz 0.97 m for 80 MHz
Baseline Length	20 m /40 m
Baseline Tilt Angle	0 Deg
Platform Altitude	5000 m - 10000 m
Center Frequency	350 MHz

X-BAND SYSTEM PARAMETERS

Parameter	Value
Peak Transmit Power	8 KW
Bandwidth	80/160 Mhz
Pulse Length	40 µsec
Sampling	8/4 BFPQ @ 160 MHz 8 bit for 80 MHz
Antenna Size	1.5 m x 0.035 m
Antenna Gain at Boresight	26.5 dBi
Antenna Look Angle	27 - 60 Deg
Antenna Boresight	60 Deg
Wavelength @ Center Frequency	0.031 m for 160 MHz 0.031 m for 80 MHz
Baseline Length	2.5 m/5 m or 1.3m/ 2.6m
Baseline Tilt Angle	0 Deg or 45 Deg
Platform Altitude	5000 m - 10000 m

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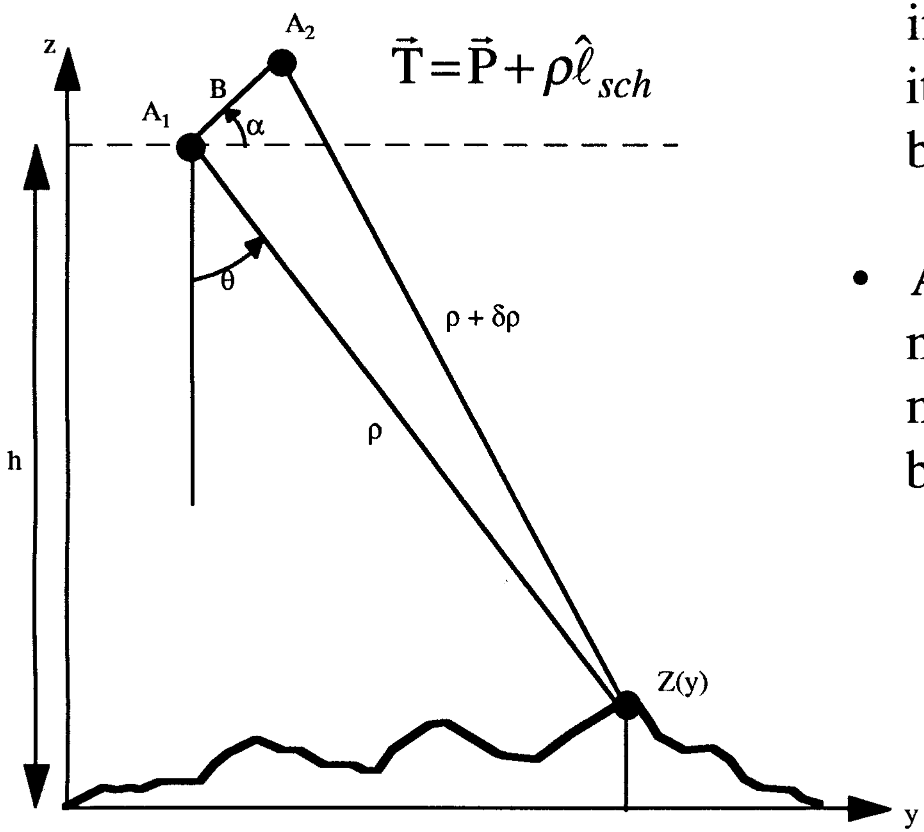
Baseline Calibration Objective



$$\vec{T} = \vec{P} + \rho \hat{\ell}_{sch}$$

- Need to determine baseline length, B and baseline attitude angle, α.

- In order to obtain accurate interferometrically derived DEMs it is essential to have very accurate baseline knowledge.

- A priori estimates of the baseline measured on the ground in general may not achieve the required accuracy because
  - phase center of antenna differs from geometric center
  - baseline may change from ground to in flight conditions (.e.g due to temperature and pressure differences)
  - accuracy of ground based measurements may not meet mapping required accuracy

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Aircraft Position Determination & Measurement Systems

- High accuracy platform position and orientation required
  - Position to ~ 10 cm, altitude to ~ 25 cm.
  - Attitude (yaw, pitch, roll) to ~ 15 arc seconds.
- Honeywell Embedded GPS Inertial Navigation Units (EGI) (twin units)
  - 5 channel GPS system, high-quality INU, internal Kalman filter.
  - Precise attitude and velocity, rough GPS-only positions, smooth blended positions.
- Ashtech Z12 GPS receiver
  - Precise positions in differential mode with nearby ground station.
  - PNAV software.
- Laser Baseline Measurement System
  - Interferometric baseline length to < 1 mm and attitude to < 15 arcsecs.
- Surveyed relative positions of GPS systems on aircraft
  - Accurate to several centimeters or better.
- Kalman Filter used to estimate aircraft state
  - Combines position and velocity data.
  - Accounts for varying uncertainties and temporal spacing.

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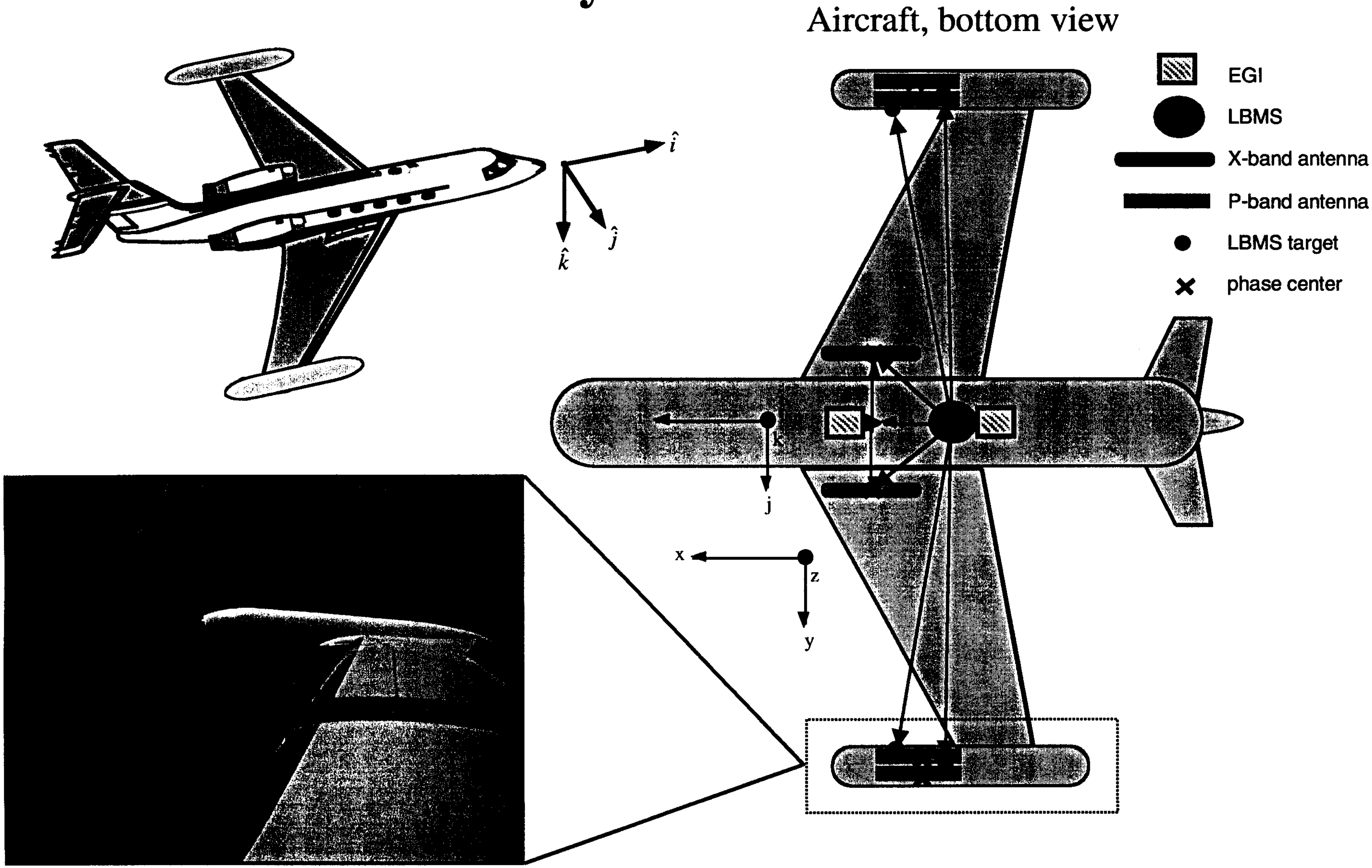
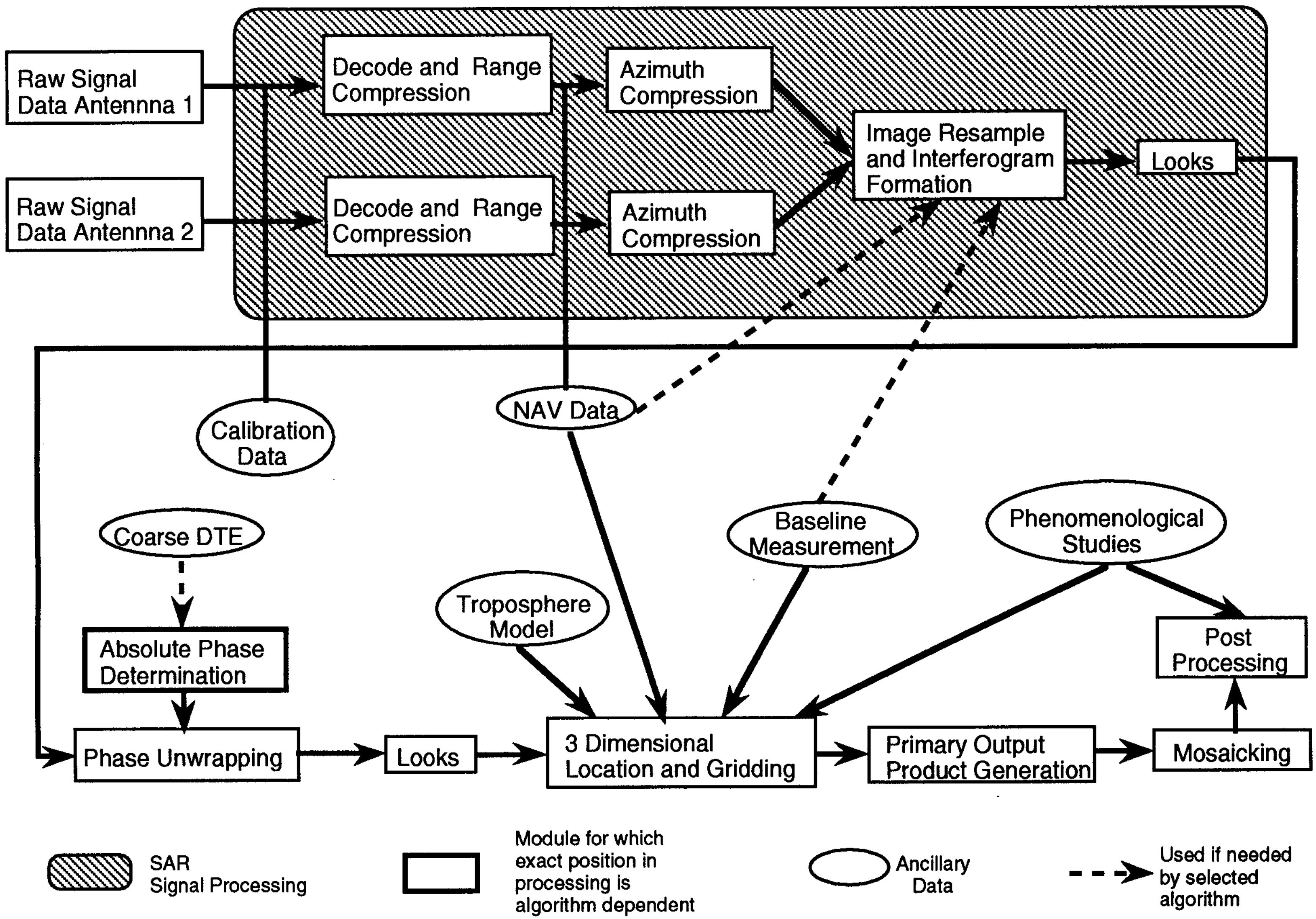
Aircraft System Illustration



Interferometric Processing



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Baseline Estimation Methodology

- Use differences between expected and and measured target positions to estimate a correction to the baseline.
  - Allow for estimation of position, range and phase errors during baseline estimation in event other parameters are not known adequately *a priori*.
  - Allow use of multiple data sets (e.g. different altitudes, different days) for baseline estimation
- Use least squares procedure to solve for baseline correction based on three dimensional imaging and processing geometry.
  - Algorithm must include knowledge of exactly how data is processed e.g. motion compensation, atmospheric corrections, etc)

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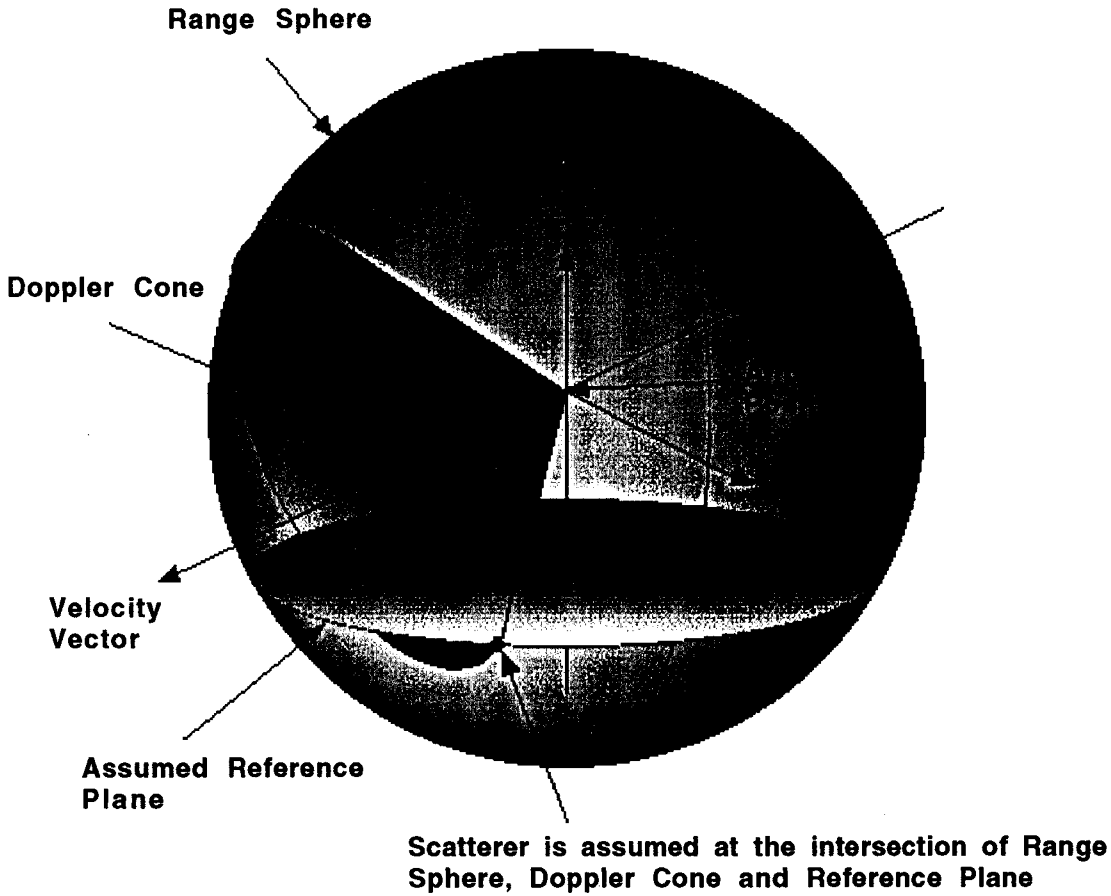
Three Dimensional Interferometric Mapping



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Baseline Parametrization

- The baseline is parametrized by its length, B, orientation angle, α, and yaw angle, κ. Assuming a velocity vector with only an along track component, a look angle of θ, and squint angle β, ($\beta = \pm 90°$ for broadside mapping, then baseline, velocity and look vectors are given by

$$\vec{B} = \begin{bmatrix} B\sin(\kappa) \\ B\cos(\alpha)\cos(\kappa) \\ B\sin(\alpha)\cos(\kappa) \end{bmatrix} \quad \vec{v} = \begin{bmatrix} v \\ 0 \\ 0 \end{bmatrix} \quad \hat{\ell} = \begin{bmatrix} \cos(\beta) \\ \mu\sin(\theta) \\ -\cos(\theta) \end{bmatrix} \quad \mu = \sqrt{1 - \left(\frac{\cos(\beta)}{\sin(\theta)}\right)^2}$$

- We define the following functions

$$g\sin(\theta,\alpha,\beta) \equiv \cos(\alpha)\sin(\theta)\mu - \sin(\alpha)\cos(\theta)$$

$$g\cos(\theta,\alpha,\beta) \equiv -\sin(\alpha)\sin(\theta)\mu - \cos(\alpha)\cos(\theta)$$

$$g\tan(\theta,\alpha,\beta) \equiv \frac{g\sin(\theta,\alpha,\beta)}{g\cos(\theta,\alpha,\beta)}$$

which for broadside mapping ($\beta = \pm 90°$) reduces to

$$g\sin(\theta,\alpha,\beta) = \sin(\theta - \alpha)$$

$$g\cos(\theta,\alpha,\beta) = -\cos(\theta - \alpha)$$

$$g\tan(\theta,\alpha,\beta) = \tan(\theta - \alpha)$$

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Least Squares Estimation I

- Baseline estimation is done using least squares with a vector of observations given by the differences between interferometrically determined target locations and their surveyed positions (2-5 cm accuracy).

$$\vec{O}_i = \begin{bmatrix} s_m - s_s \\ c_m - c_s \\ h_m - h_s \end{bmatrix}$$

where subscripts s,m denoted measured and surveyed positions and 1≤i≤N.

- The vector of observations can be truncated to use only cross track or vertical measurements is desired. The observations are weighted by covariance estimates derived from the interferometric correlation.

$$C_i = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \left(\frac{\partial c}{\partial \phi}\right)^2 \sigma_\phi^2(\gamma) & 0 \\ 0 & 0 & \left(\frac{\partial h}{\partial \phi}\right)^2 \sigma_\phi^2(\gamma) \end{bmatrix}$$

Least Squares Estimation II

- The vector of parameters to be solved for is

$$\vec{P} = [\Delta B \quad \Delta\alpha \quad \Delta\kappa \quad \Delta\rho \quad \Delta\phi \quad \Delta P_s \quad \Delta P_c \quad \Delta P_h]^{\mathrm{t}}$$

and the least squares solution is

$$\vec{P} = \left(\sum_{i=1}^{N} A_i^{\mathrm{t}} C_i^{-1} A_i \right)^{-1} \left(\sum_{i=1}^{N} A_i^{\mathrm{t}} C_i^{-1} \vec{O}_i \right)$$

where A is the matrix of partials of the observations with respect to the parameters to be estimated.

$$A = \begin{bmatrix} \frac{\partial T_s}{\partial B} & \frac{\partial T_s}{\partial \alpha} & \frac{\partial T_s}{\partial \kappa} & \frac{\partial T_s}{\partial \rho} & \frac{\partial T_s}{\partial \phi} & \frac{\partial T_s}{\partial P_s} & \frac{\partial T_s}{\partial P_c} & \frac{\partial T_s}{\partial P_h} \\ \frac{\partial T_c}{\partial B} & \frac{\partial T_c}{\partial \alpha} & \frac{\partial T_c}{\partial \kappa} & \frac{\partial T_c}{\partial \rho} & \frac{\partial T_c}{\partial \phi} & \frac{\partial T_c}{\partial P_s} & \frac{\partial T_c}{\partial P_c} & \frac{\partial T_c}{\partial P_h} \\ \frac{\partial T_h}{\partial B} & \frac{\partial T_h}{\partial \alpha} & \frac{\partial T_h}{\partial \kappa} & \frac{\partial T_h}{\partial \rho} & \frac{\partial T_h}{\partial \phi} & \frac{\partial T_h}{\partial P_s} & \frac{\partial T_h}{\partial P_c} & \frac{\partial T_h}{\partial P_h} \end{bmatrix}$$

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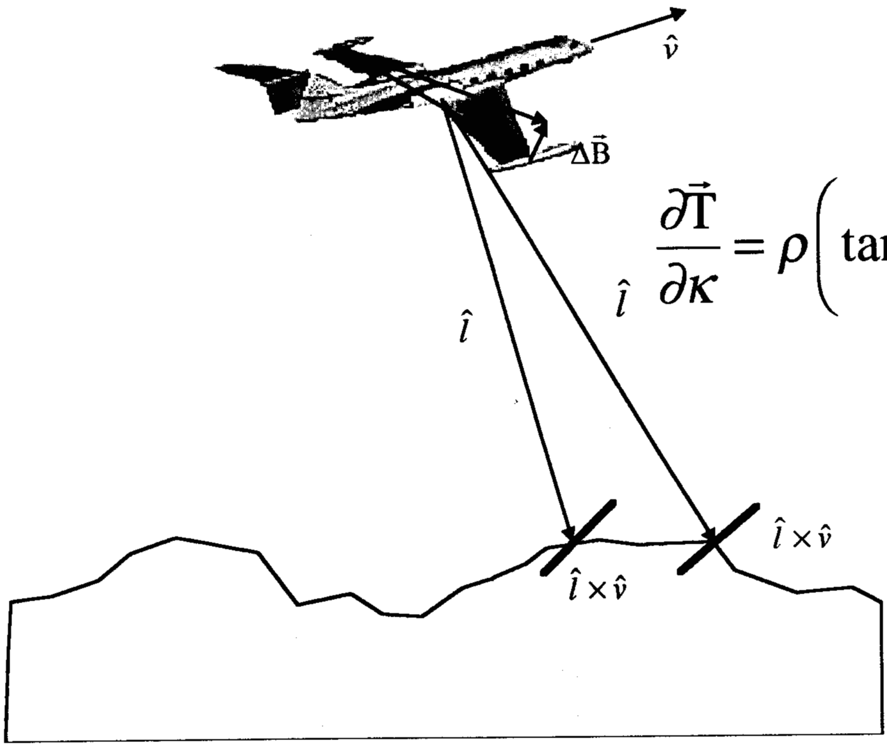
Baseline Sensitivity

$$\frac{\partial \vec{\mathrm{T}}}{\partial B} = \frac{\rho}{B}\left(g\tan(\theta,\alpha,\beta) + \frac{\tan(\kappa)\cos(\beta)}{g\cos(\theta,\alpha,\beta)} \right) \begin{bmatrix} 0 \\ -\cos(\theta) \\ -\mu\sin(\theta) \end{bmatrix}$$



$$\frac{\partial \vec{\mathrm{T}}}{\partial \kappa} = \rho\left(\tan(\kappa) g\tan(\theta,\alpha,\beta) - \frac{\cos(\beta)}{g\cos(\theta,\alpha,\beta)} \right) \begin{bmatrix} 0 \\ \cos(\theta) \\ \mu\sin(\theta) \end{bmatrix}$$

$$\frac{\partial \vec{\mathrm{T}}}{\partial \alpha} = \rho \begin{bmatrix} 0 \\ \cos(\theta) \\ \mu\sin(\theta) \end{bmatrix}$$

- Baseline errors give position errors along perpendicular to the line of sight and velocity vectors.

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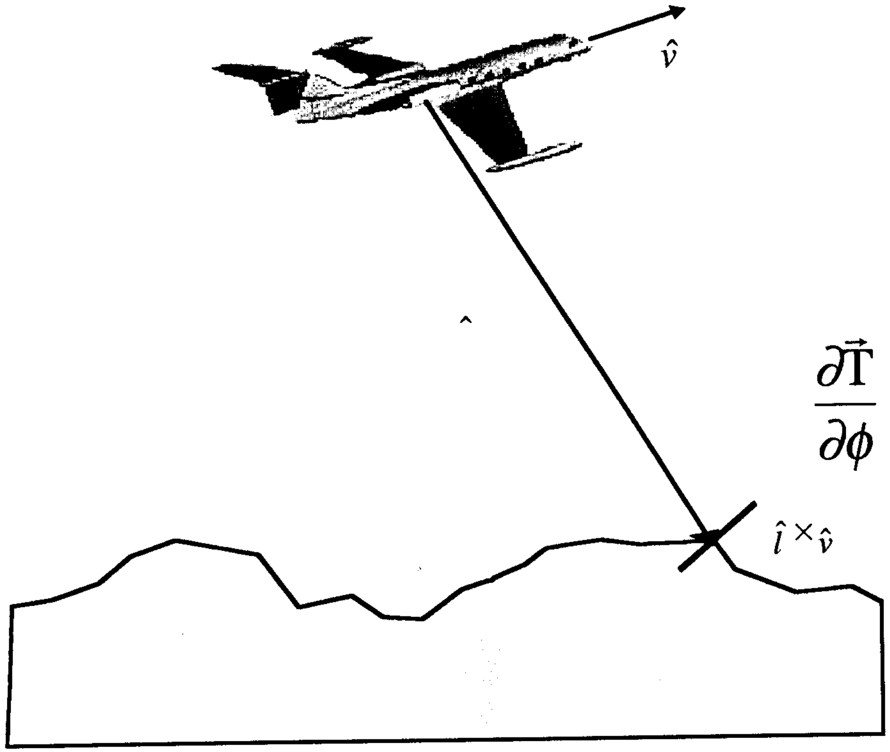
Phase Sensitivity



$$\frac{\partial \vec{T}}{\partial \phi} = \frac{-\lambda \rho}{a 2\pi B g \cos(\theta, \alpha, \beta) \cos(\kappa)} \begin{bmatrix} 0 \\ \cos(\theta) \\ \mu \sin(\theta) \end{bmatrix}$$

- Phase errors give position errors along perpendicular to the line of sight and velocity vectors.

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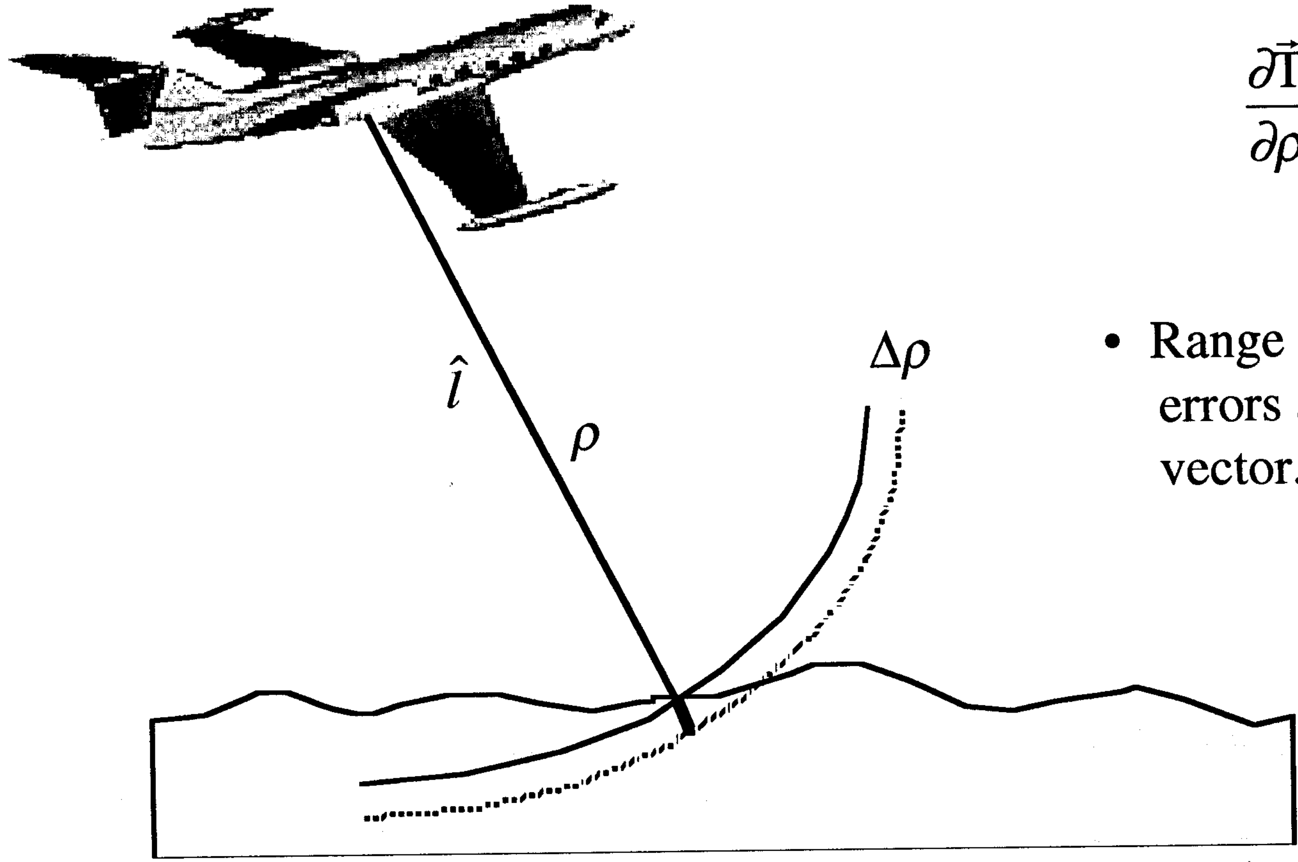
Range Sensitivity



$$\frac{\partial \vec{T}}{\partial \rho} = \begin{bmatrix} \cos(\beta) \\ \mu \sin(\theta) \\ -\cos(\theta) \end{bmatrix}$$

- Range errors give position errors along the line of sight vector.

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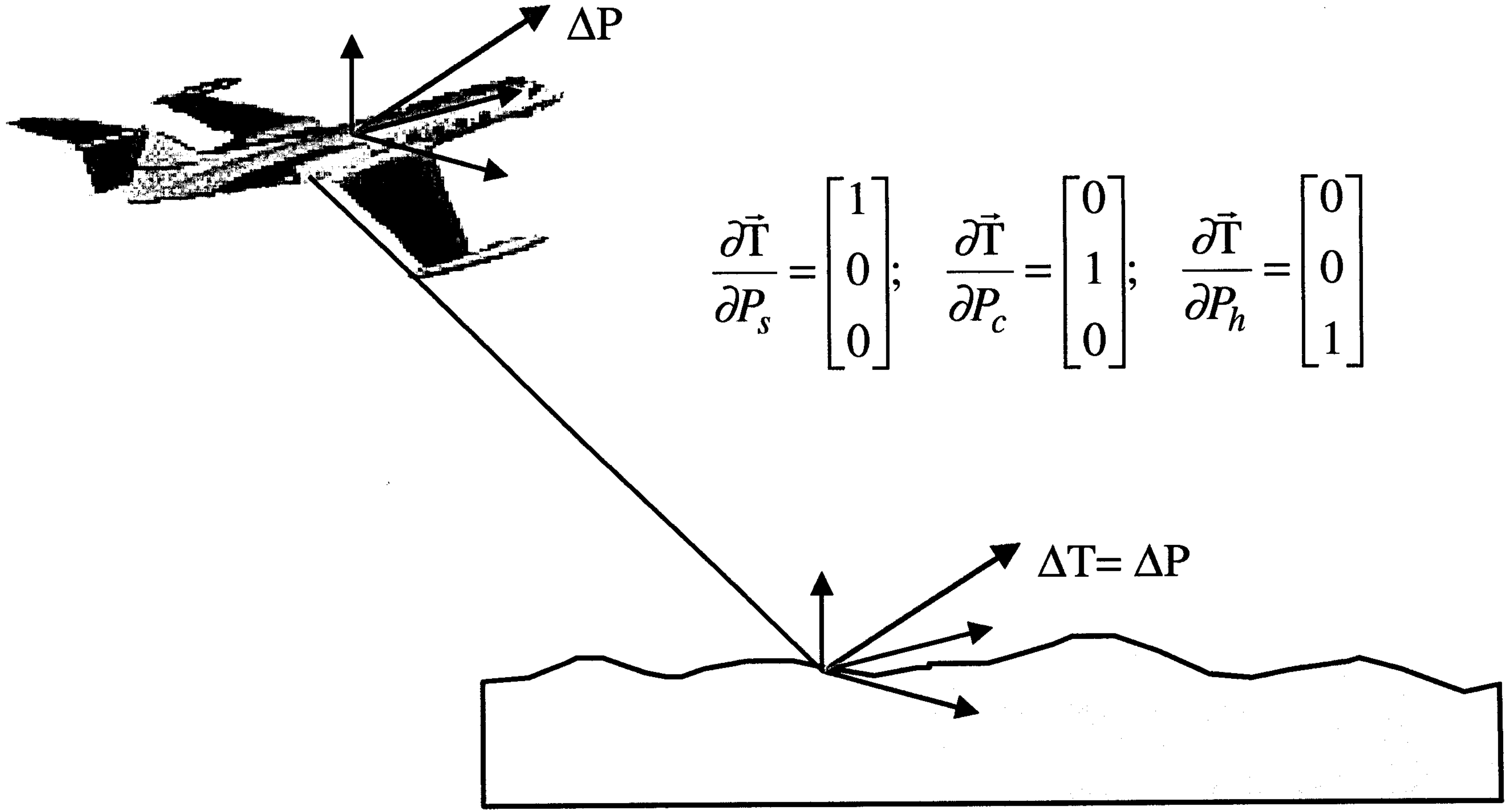
Platform Position Sensitivity



$$\frac{\partial \vec{T}}{\partial P_s} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}; \quad \frac{\partial \vec{T}}{\partial P_c} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}; \quad \frac{\partial \vec{T}}{\partial P_h} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

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Derivative Correction for Spherical Earth

- Since the interferometrically derived fiducal point position measurements are in a spherical coordinate system we must correct the tangent plane position (primed) derivatives to derivatives that represent position changes with respect to the spherical coordinate system (unprimed).

$$\frac{\partial s_T}{\partial \zeta} = \frac{r_a}{s_T'^2 + (r_a + h_T')^2} \left\{ (r_a + h_T') \frac{\partial s_T'}{\partial \zeta} - s_T' \frac{\partial h_T'}{\partial \zeta} \right\}$$

$$\frac{\partial c_T}{\partial \zeta} = \frac{r_a}{\sqrt{s_T'^2 + (r_a + h_T')^2}} \left\{ \frac{\partial c_T'}{\partial \zeta} - \frac{c_T'}{(r_a + h_T)^2} \left[\left(c_T' \frac{\partial c_T'}{\partial \zeta} + s_T' \frac{\partial s_T'}{\partial \zeta} \right) + (r_a + h_T') \frac{\partial h_T'}{\partial \zeta} \right] \right\}$$

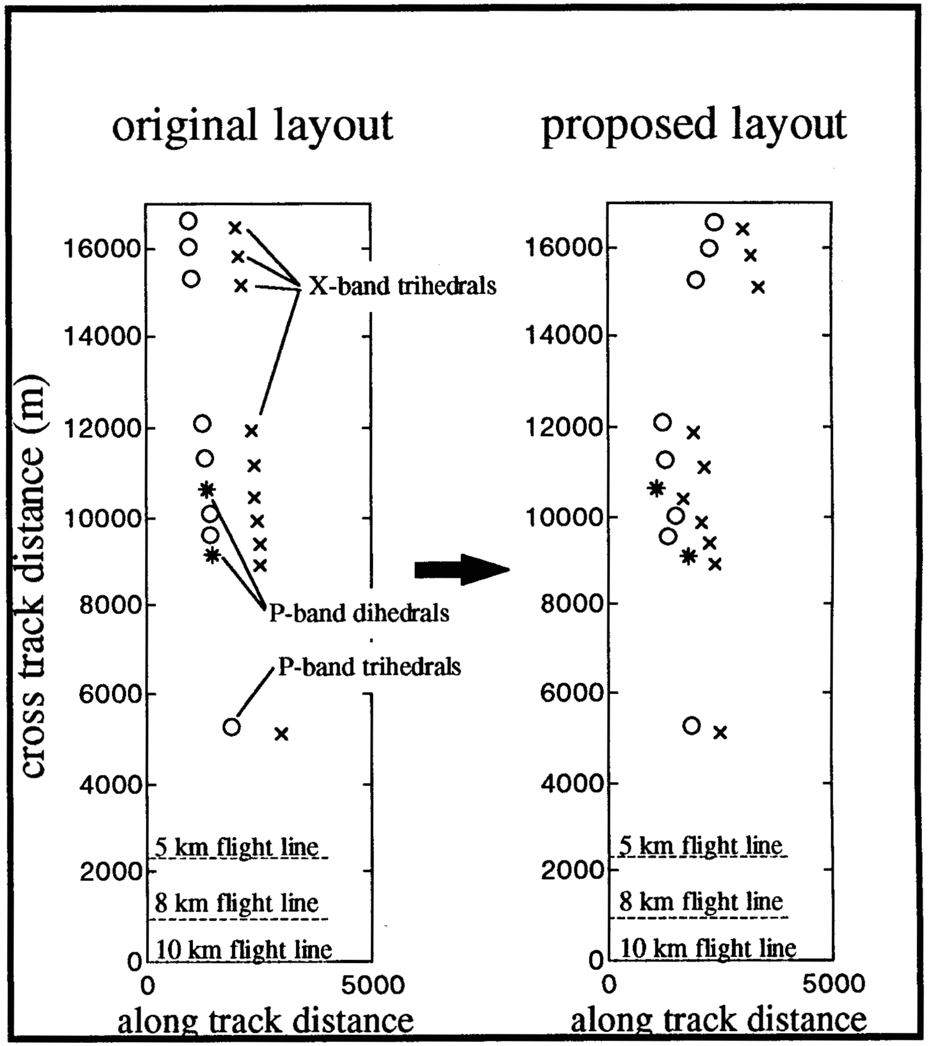
$$\frac{\partial h_T}{\partial \zeta} = \left(\frac{r_a + h_T'}{r_a + h_T} \right) \frac{\partial h_T'}{\partial \zeta} + \frac{1}{r_a + h_T} \left(c_T' \frac{\partial c_T'}{\partial \zeta} + s_T' \frac{\partial s_T'}{\partial \zeta} \right)$$

Calibration Site

Main Target Array

- Base at Hunter-Liggett chosen as the primary calibration site
- Calibration targets placed to minimize topographic height variations and maximize estimation sensitivity
- Additional targets on opposite side and within-scene along track
- Corner reflectors have been deployed

<u>Deployed:</u>
12 X-band trihedrals



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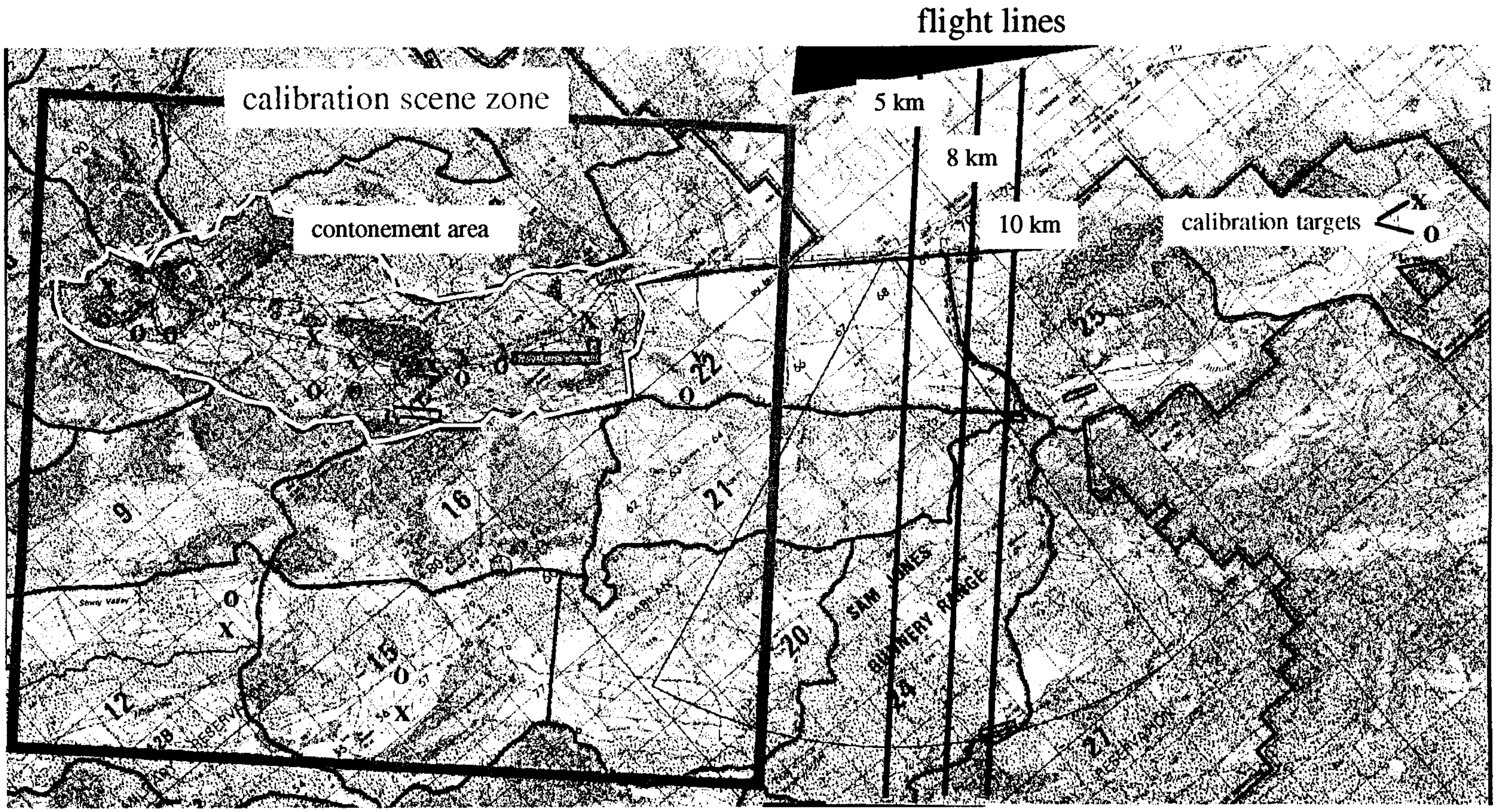
Map of Hunter Liggett



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Position Offsets Before Calibration

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Position Offsets After Calibration and Baseline Errors Estimates

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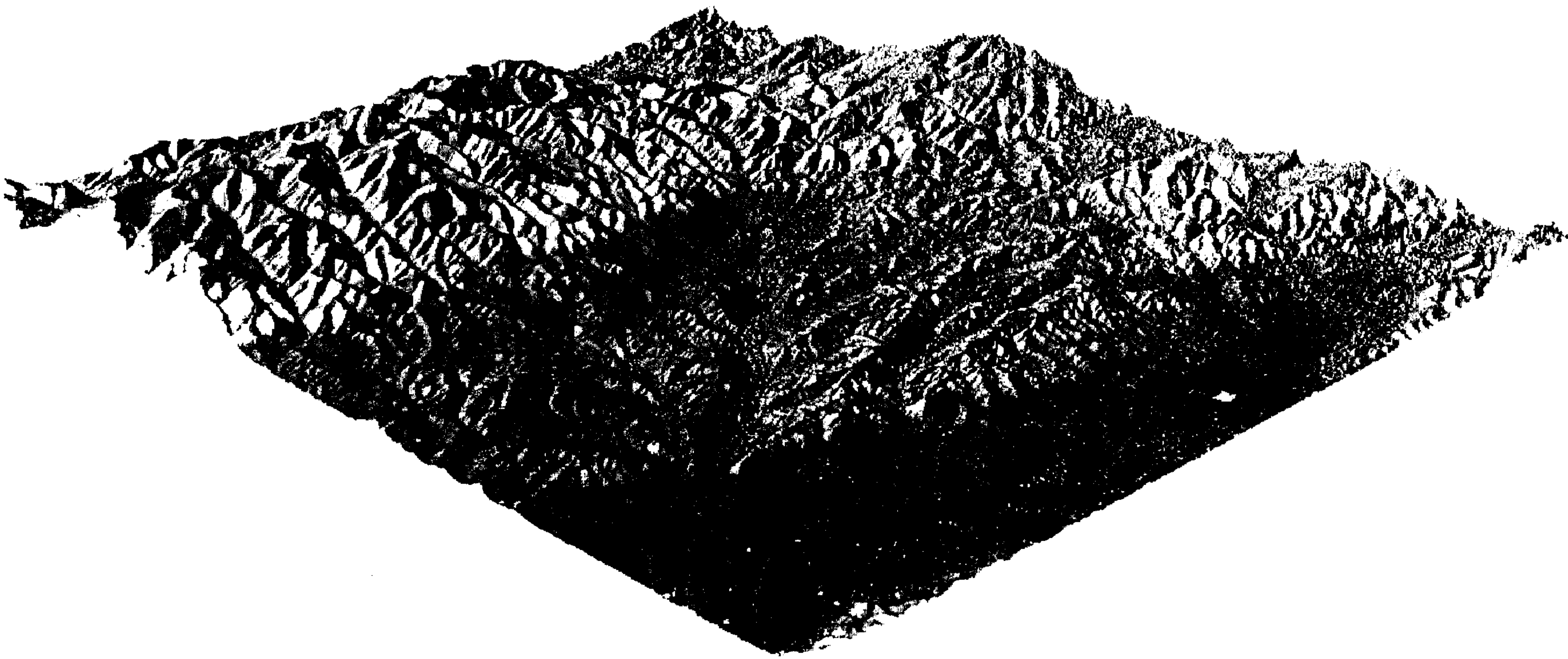
Perspective View with Shaded Relief Overlaid



Conclusions

- Accurate baseline estimates for aircraft systems can be obtained with a well arranged set of corner reflectors.
- The X-Band GeoSAR baseline was estimated to an accuracy of .1 cm.